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FINDING YOUR WATCH AND LOOSING YOUR BEARINGS

By: Nick Komninos of Superior Signal Company, Inc., Spotswood NJ

ABSTRACT
This paper introduces the practitioners of condition monitoring in machinery to the concept of ultrasonic inspection. The basic theory of ultrasound and some typical applications will show how ultrasonic inspection complements vibration analysis and gives the user one more way to determine the health of machinery.

A number of examples of the different ways to translate the high frequency sound to the sonic range and the associated spectra will be presented.

INTRODUCTION

Suppose you found a watch the kind that ticks. You may put it by your ear to hear if it works, or use an instrument to hear the ticktack as it runs. Hearing this sound though you cannot tell if the watch is set correctly or if it keeps time accurately. The ticktack only tells you that it works. Nothing more.

Now suppose that you are even luckier, and you are the person in charge of predictive maintenance at your facility. You have been using among other things, vibration analysis to stay one step ahead of failures in machinery that moves. You have a vibration analyzer, the software, and you are trained in the theory and applications of the technology. Still there are some failures that you cannot see happening far in the horizon.

You may know that you have a problem let us say at a particular pillow block. You may even know if it is caused by an inner or an outer race fault of the bearing there, but you wished you could see this just a little earlier, just before the vibration analysis picked it up. Is that possible? What can you do?

Well all you need to do is listen. Not to your lucky watch, but to the bearing which may be screaming for your attention if you could only hear it. Unlike your watch, it is screaming above your capability to hear, in the ultrasonic range of sound.

Do not confuse sound and vibration. They are similar yet very different phenomena.

Sound is a microscopic oscillation in the molecular level of a substance. Vibration is a macroscopic oscillation of structures, that is things that move, and behind all things that move, is a force that is pushing or pulling them. Vibration analysis attempts to measure this force by measuring the acceleration of a machine member with an accelerometer.

Sound on the other hand is the precursor of this vibration, this force. This sound comes from among other things friction, which is an atomic force. Friction is a generator of sound in solids as well as in gasses. In gasses, turbulence makes the molecules collide with each other in random ways causing them to oscillate and generate sound waves.

What are the properties of sound and what exactly is it in the first place? Sound in air is a pressure wave. Air molecules are moving in tight or loose bunches along the direction of propagation. Tight bunches, like a wind gast, are higher pressure where loose bunches are lower pressure. Our ear responds to these pressure fluctuations and our brain interprets them accordingly. However just like our eyes that can only see a part of the light spectrum, our ears can hear only a part of the sound spectrum.

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The range of frequencies the human ear can respond to is called the sonic range. Frequencies below the sonic range are called Infrasonic, where frequencies above are called Ultrasonic. Few animals in nature can generate or respond to all these sound ranges. For example elephants can make and hear infrasonic sounds and they use this ability to communicate in very large distances. Bats on the other hand have the ability to generate and hear ultrasound and use this ability to navigate in the dark and to locate their food. To humans infrasonic and ultrasonic sounds are just like infrared and ultraviolet light respectively.

Since sound is a wave, it has all the properties of waves. Waves are characterized by a frequency of oscillation, speed of propagation and wavelength. The speed of propagation is set by the medium where the sound is propagating. Dense materials in general allow the sound to move faster through them, where less dense do the opposite. Frequency, wavelength and speed are related to each other through the formula:

$$f\lambda=\nu \quad (1)$$

Where f is the frequency, λ is the wavelength and ν is the speed of propagation.

In air the speed of sound is 331.3m/s at 0°C.

The speed varies as the atmospheric conditions vary, but for all practical purposes it is close to this number.

So why do elephants have big ears? They do because they need to hear infrasonic sounds which have large wavelengths. Herds communicate over distances of a few miles using low frequency waves whose wavelengths are very long.

This allows the wave to bend around objects and travel long distances. In contrast to elephants, bats use very high frequency bursts of sound to locate and classify insects in the dark. High frequency sound waves do not bend around objects and propagate and reflect in straight lines. This allows the bat to navigate and echo locate objects without the benefit of sight. Both species find their bearings using sound.

Another species, known to biologists as the Hardhatus Toolbeltus Overworktus, HTO for short, uses ultrasound to locate and repair leaks in human industrial facilities that have a multitude of pipes and by extension many sources of sound. However ultrasound can not be heard by HTOs. So in order to hear and interpret the sound we need to convert it to the sonic range of frequencies so they can hear it. How do we do this? The traditional way to do this is to use heterodyning. Heterodyning as the word implies is the mixing of two waves. The mixing of two waves produces the sum and the difference of the original waves, which allows the shifting of a high frequency sound to the sonic range.

The mathematical formula used for this process is:

$$A\cos(\omega_1 t)B\cos(\omega_2 t)=$$
$$=1/2\{AB\{\cos(\omega_1+\omega_2)t\}\}+1/2\{AB\{\cos(\omega_1-\omega_2)t\}\} \quad (2)$$

Where:
A is the amplitude of the first wave,
B is the amplitude of the second wave,
ω_1 is the frequency of the first wave,
ω_2 is the frequency of the second wave

As an example lets assume that we have a bearing that is generating a sound signal of 31kHz to 33kHz. Since humans can hear up to 20kHz and HTOs maybe 16kHz, this sound cannot be heard. Mixing a 30kHz constant frequency wave with this signal we will get a

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difference of 1kHz to 3kHz and a sum of 61kHz to 63kHz. The 1kHz to 3kHz information is very easy to hear and interpret. The sum is much higher, cannot be heard, and it is discarded.

The inner-workings of heterodyning consist of three elements. These are the mixer (X), the local oscillator (LO), and the low-pass filter (LP). Figure 1 shows the block diagram of the heterodyne translator.

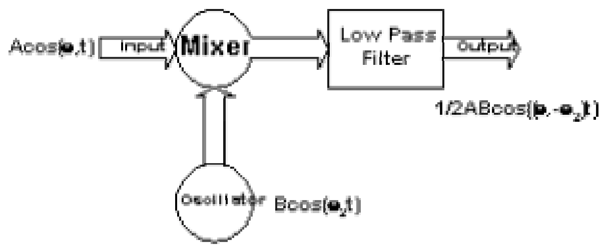

Figure 1.
Block diagram of heterodyne translator

Figure 2 shows a typical spectrum of the signals in and out of the heterodyne mixer. In this figure the signal is at 21.50kHz and the LO is at 30.30kHz. The sum and the difference are shown at 51.80kHz and at 8.80kHz respectively. When this composite signal is passed through the low pass filter only the difference the 8.80kHz, will appear at the output.

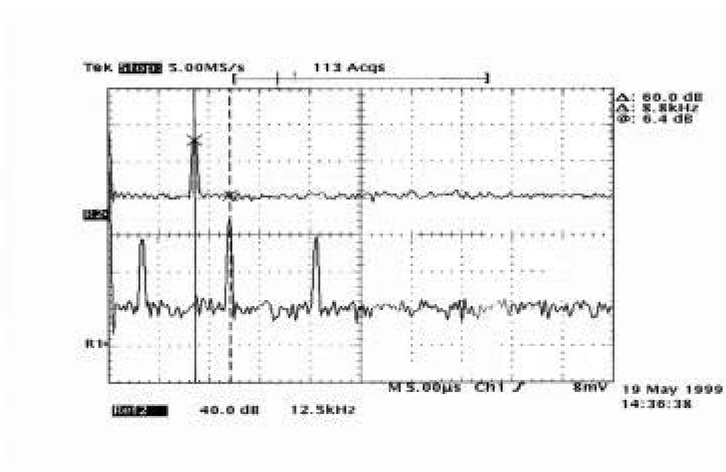

Figure 2

Spectrum of two frequencies heterodyned

This technique of band shifting is very useful when we need to inspect bearings. The old way of listening with the screwdriver is not useful when it comes to hearing high frequencies. It is just like putting the watch you have just found by your ear. Can you hear it tic? Suppose it does. Does this fact tell you if it works well and if it keeps time correctly? No!

To interpret this high frequency information we need a spectrum analyzer. Vibration analyzers can also be used since they are specialized spectrum analyzers. They are used in conjunction with accelerometers to show the oscillation modes of a machine member at the point where the accelerometer is connected. Since most accelerometers have a limited frequency response, the majority of inexpensive vibration analyzers do not have the ability to show spectra much higher than 20kHz.

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However it is this high frequency sound that will help you find your bearings. High frequency sound is the precursor of vibration. Using an ultrasonic detection instrument as the sensor for a vibration analyzer will allow you to see spectra generated by friction a little earlier than you can see them with vibration analysis. Naturally you need to be able to see more than just a narrow spike shifted to the sonic range. Shifting a band of frequencies is just as easy provided you do not try to see more than the bandwidth of the low pass filter. Figure 3 shows the shifting of a band of frequencies into the sonic range. If the range of frequencies of interest were larger than the LP bandwidth, a portion of the information would be lost. For repetitive events though such as rotating shafts this is not a problem because tuning the ultrasonic instrument a little higher will show the portion that was missed before.

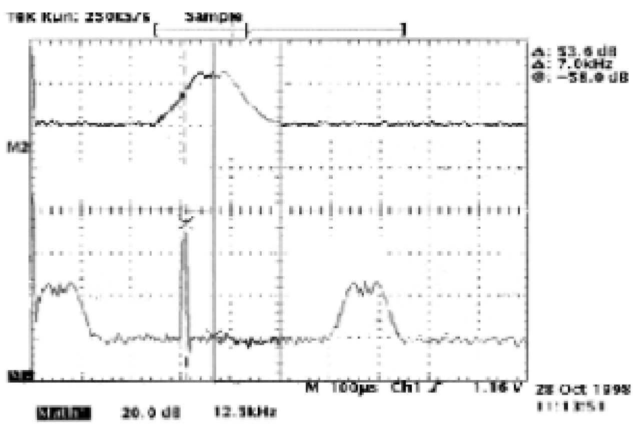

Figure 3

Shifting of a band of frequencies

The LP filter is in a sense the window that moves over the spectrum of the high frequency sound and the mixer moves it down to another band.

The new band of frequencies that we can analyze now with our vibration analyzer will contain spectra within an analysis range set in the parameters of the analyzer.

If the analyzer is set to show the range of 0Hz to 1kHz and we see a peak at 724.10Hz, we must know the LO frequency to determine where this frequency came from.

If as in the example of Figure 2 the LO is set at 30.30kHz then the original sound was from 31.02410kHz This is 11kHz higher than the sonic range.

Machines do not just turn or move for no reason. The work that is done by a machine usually has an effect on the sounds that it generates. Some of these sounds may be available at pillow blocks or other points throughout the machine.

Internal leakage for example that may aggravate wear at some point can be correlated now because the ultrasonic instrument can hear the hidden sound of the turbulent flow and display it in the analyzer together with the frictional sounds. Mysterious failures now can be found and corrected. Figure 4 is a typical "leak" that can be found internally or externally in machinery.

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Figure 5 is a typical signal generated by a leak. Notice the change in amplitude as time increases. Frequency also changes but it is difficult to see in this time scale. Figure 6 shows in the upper scale the original signal and in the lower trace the translated.

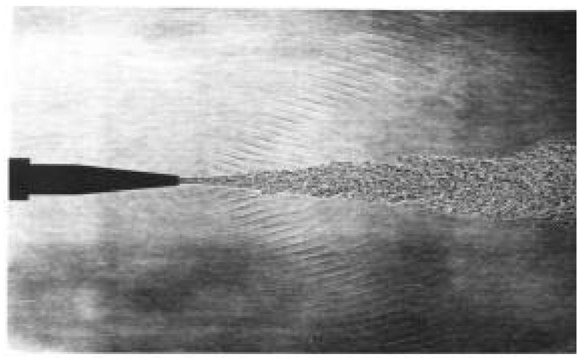

Figure 4

Typical Leak

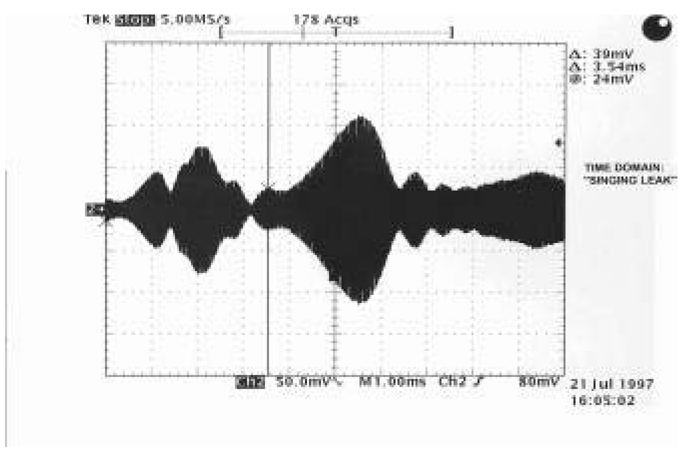

Figure 5

Typical signal from a leak

Figure 5 is a typical signal generated by a leak. Notice the change in amplitude as time increases. Frequency also changes but it is difficult to see in this time scale. Figure 6 shows in the upper scale the original signal and in the lower trace the translated.

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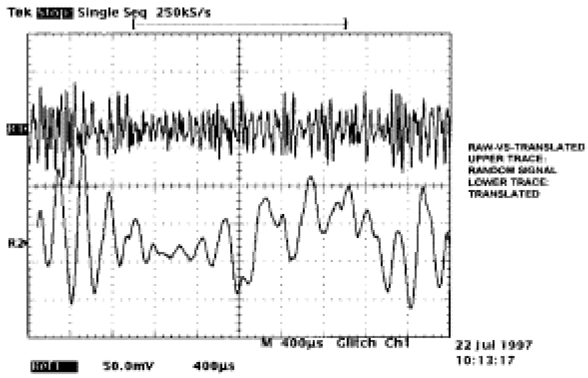
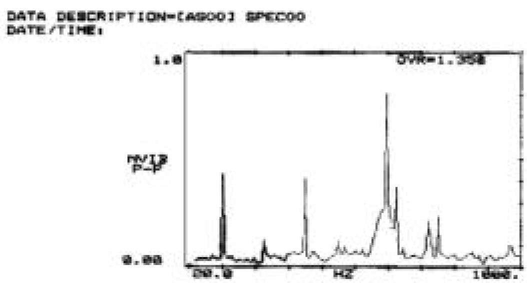


Figure 6

Upper scale = original signal
Lower trace = translated signal

Understanding how this process is done we can put it all together. Figure 7 shows the spectrum taken from a gearbox-motor combination. At a first glance this seems to be a 0Hz to 1kHz vibration spectrum. However it is a spectrum translated from 38kHz. 0Hz in this spectrum corresponds to 38kHz, and 1kHz corresponds to 39kHz. The instrument used to capture this spectrum was tuned to 38kHz.



FREQ	PEAK	FREQ	PEAK	FREQ	PEAK	FREQ	PEAK
64.95	.06032	380.0	.06954	[illegible]	0.9035	753.3	0.2527
94.25	.07616	456.6	0.1471	626.8	0.4467	795.1	.09225
121.0	0.4371	480.0	.09482	650.0	.09008	845.1	0.1089
243.3	0.1505	510.0	.07744	675.0	.08391	904.7	.08115
358.5	0.4261	525.8	0.1135	724.1	0.2948	964.7	0.1592

Figure 7

Gearbox, High frequency spectrum, translated

A frequency in the signals from the gearbox at 38kHz produces a difference of zero, and a sum of 76kHz. This zero is the zero frequency in our analyzer. Tuning the ultrasonic instrument to another frequency will shift this zero up or down. Using this technique one can tune at any band. The limiting factors are the transducer used, and the frequency range of the tuner.

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SUMMARY
It is important to appreciate the importance of incorporating ultrasound in existing or new applications of condition monitoring. Understanding the principles of sound propagation, and translation with heterodyning, new information can be seen and analyzed with the same techniques used in vibration analysis. So the next time you are called to diagnose a bearing problem, do not just put your naked ear to it, because just like the watch you found, it may be running but not on time.

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Nick Komninos is a senior project engineer with the Superior Signal Company in Spotswood NJ USA.

In this capacity he has been involved in the design and applications of ultrasonic leak detectors and bearing condition instruments for ten years.

Mr. Komninos received a Bachelor of Science in Mathematics/Physics (1982) and a Masters of Science in Electrical Engineering (1986) both from the University of New Mexico. He is a member of IEEE and has a number of publications in the area of ultrasonic leak detection on the theory and practice of the technology.

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